

Geophysical Research Letters



RESEARCH LETTER

10.1029/2020GL091279

Key Points:

- Bottom trawling disturbance on the deep seafloor depletes organic matter through erosion and degradation, hampering its preservation
- A 2-month seasonal trawling closure is insufficient to restore the seafloor and it is estimated that it would take decades to recover
- Bottom trawling causes organic carbon losses from the seafloor comparable to those generated on land by tillage of agricultural fields

Supporting Information:

- Supporting Information S1

Correspondence to:

S. Paradis,
sarah.paradis@uab.cat

Citation:

Paradis, S., Goñi, M., Masqué, P., Durán, R., Arjona-Camas, M., Palanques, A., & Puig, P. (2021). Persistence of biogeochemical alterations of deep-sea sediments by bottom trawling. *Geophysical Research Letters*, 48, e2020GL091279. <https://doi.org/10.1029/2020GL091279>

Received 23 OCT 2020
Accepted 3 DEC 2020

© 2020. The Authors.

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial License](https://creativecommons.org/licenses/by-nc/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

Persistence of Biogeochemical Alterations of Deep-Sea Sediments by Bottom Trawling

S. Paradis^{1,2,3} , M. Goñi⁴ , P. Masqué^{1,2,5,6} , R. Durán³ , M. Arjona-Camas^{3,7} , A. Palanques³ , and P. Puig³ 

¹Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, Bellaterra, Spain, ²Physics Department, Universitat Autònoma de Barcelona, Bellaterra, Spain, ³Marine Sciences Institute, Consejo Superior de Investigaciones Científicas, Barcelona, Spain, ⁴College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA, ⁵School of Natural Sciences, Centre for Marine Ecosystems Research, Edith Cowan University, Joondalup, WA, Australia, ⁶International Atomic Energy Agency, Principality of Monaco, Monaco, ⁷Department of Earth and Ocean Dynamics, University of Barcelona, Barcelona, Spain

Abstract Bottom trawling grounds have been expanding to deeper areas of the oceans since the mid-XXth century, and mitigating strategies aimed to protect fish stocks, such as temporal trawling closures, have recently been implemented. Here we investigated the biogeochemical properties of sediment from a deep-sea trawling ground in Palamós Canyon (NW Mediterranean) to assess the effects of a 2-months trawling closure in the recovery of sedimentary organic matter. In comparison to untrawled areas, the continuous erosion and sediment mixing in trawling grounds led to coarser reworked sediments impoverished in organic carbon (~30% loss) and promoted the degradation of labile compounds (52–70% loss). These impacts persisted after the temporal trawling closure, highlighting that this management strategy is insufficient to restore the seafloor. Considering the continuous expansion of bottom trawling grounds, this activity could have significant and irreversible biogeochemical impacts on ocean margins at a global scale, hampering their carbon burial capacity.

Plain Language Summary Bottom trawling grounds have been expanding to deeper areas of the oceans since the mid-XXth century, causing substantial effects to fish populations. In order to reduce this impact, new management strategies have been introduced, such as establishing temporal trawling closures to allow fish populations to recover. Bottom trawling not only poses a threat to fish populations but also to the seafloor, since the continuous contact of trawling gear on the bottom erodes large volumes of sediment and reduces the amount and quality of organic matter. In this study, we assessed the effect of a 2-months trawling closure in deep-sea bottom trawling grounds in Palamós Canyon (NW Mediterranean) by collecting sediment samples in trawled and untrawled areas during different seasons. Our results show that sediment samples in the trawled site had substantially lower organic matter contents than in the untrawled site, and the remaining organic matter had poor nutritional quality. These impacts persisted after the temporal trawling closure, highlighting that this management strategy is insufficient to restore the seafloor. Considering the continuous expansion of bottom trawling grounds, this activity could have significant and irreversible impacts in organic matter available for benthic species in ocean margins at a global scale.

1. Introduction

Continental margins are the continuum between the land and the ocean, and they are responsible for the majority of both burial and remineralization of organic carbon (OC) in the ocean (Dunne et al., 2007). However, biogeochemical cycles of organic matter in continental margins are altered by several anthropogenic activities (Bauer et al., 2013). Amongst those, bottom trawling is considered to be the most harmful and has the potential to alter the biogeochemistry of continental margins at a global scale given its widespread extension, high frequency, and direct impacts on the seafloor (Eigaard et al., 2017; Ferguson et al., 2020; Hayes et al., 2018; Keil, 2017).

The continuous contact of bottom trawling gear on the seafloor causes a variety of physical impacts (Martin et al., 2014b; Oberle et al., 2018). In muddy seafloor environments, trawling gear can create long-lasting

trawl marks, overturn sediment, and cause resuspension (O'Neill & Ivanović, 2016; Palanques et al., 2014). Resuspended sediments by bottom trawling is often exported by ambient currents, leading to significant erosion in fishing grounds (Oberle et al., 2016a). These disturbances modify the biogeochemistry of marine sedimentary environments, but the effects on the carbon stock stored in the seafloor is still uncertain (Legge et al., 2020) due to the variable alterations on organic matter content and remineralization (Ferguson et al., 2020; Hale et al., 2017; Palanques et al., 2014; van de Velde et al., 2018).

Many of these previous studies were carried out in muddy continental shelves, which are areas with high sediment and organic matter accumulation rates from both terrestrial and marine origins (Gordon & Goñi, 2004; Hedges & Keil, 1995) that can abate the physical and biogeochemical alterations caused by bottom trawling on the seafloor. Additionally, shallow environments are frequently impacted by natural processes, such as storm waves, which can resuspend similar volumes of sediment and organic matter compared to bottom trawling (Ferré et al., 2008; Pusceddu et al., 2005). However, the growing demand of fish and the depletion of shallow-water fishing stocks have driven the expansion of bottom trawling grounds to deeper environments since the 1950s, fueled by technological advances and subsidies. Bottom trawling now generally occurs at >500 m water depth and can extend to more than 1,500 m (Watson & Morato, 2013). Since new and deeper areas are continuously being explored, there is an increasing urgency to understand the impacts of bottom trawling on deep-sea environments.

Deep bottom trawling grounds are usually concentrated near topographic features such as seamounts and submarine canyons, which act as ecological hotspots of many commercial species (Clark et al., 2007; Fernandez-Arcaya et al., 2017). The impacts of bottom trawling in these environments are intensified due to the low productivity and growth rates of deep-sea species, which has led to a rapid collapse of deep-sea fisheries (Norse et al., 2012). The growing concern of stock overexploitation has stimulated the implementation of management strategies, such as temporal trawling closures to allow stock rebuilding and the recruitment of juveniles (Armstrong et al., 2013). Bottom trawling impacts on deep-sea sedimentary environments are also accentuated due to the low sedimentation rates and organic matter fluxes, producing comparatively enhanced erosion and depletion of OC in sediments (Martín et al., 2014a). However, neither the mechanisms causing the reduction of organic matter nor the efficacy of seasonal trawling closures have been fully addressed.

The Mediterranean Sea supports important deep bottom trawling fisheries, mostly located in the Western basin, where virtually the whole slope is covered by bottom trawling grounds (Figure 1a). Studies aimed to understand the impacts of deep bottom trawling in this region have been centered in the vicinities of Palamós Canyon (Figure 1b), where intense bottom trawling occurs along its flanks, targeting the coveted red-and-blue deep-sea shrimp *Aristeus antennatus* (Bjørkan et al., 2020; Gorelli et al., 2016). The studies addressing the trawling-induced seafloor erosion and the associated impacts on the sedimentary organic matter (Martín et al., 2014a; Pusceddu et al., 2014; Sañé et al., 2013) mainly focused on the spatial variability in the canyon, observing comparable impacts on both canyon flanks. However, these studies did not evaluate the temporal changes in organic matter composition. Moreover, a 2-months trawling closure from early January to early March was recently established since 2013 to avoid the risk of overexploitation due to the continuous increase in fishing effort over the last decades (Bjørkan et al., 2020). This scenario provided the ideal setting to assess the effectiveness of seasonal trawling closures to restore deep-sea sedimentary environments. To achieve these objectives, sediment cores were collected from representative sites in the northern trawled canyon flank and in the southern untrawled canyon flank during different seasons (Figures 1b and S1), and at similar depths and distance from the coast to minimize the potential effects of spatial variability, since these are the main spatial factors controlling the composition and magnitude of downward particle fluxes within the canyon (Palanques et al., 2005; Martín et al., 2006, 2007). Several biomarker compound classes yielded from the oxidation of CuO were used to assess the quantity, composition, source, and degree of degradation of sedimentary organic matter (e.g., Goñi et al., 2013; Tesi et al., 2012) during trawling and closure periods.

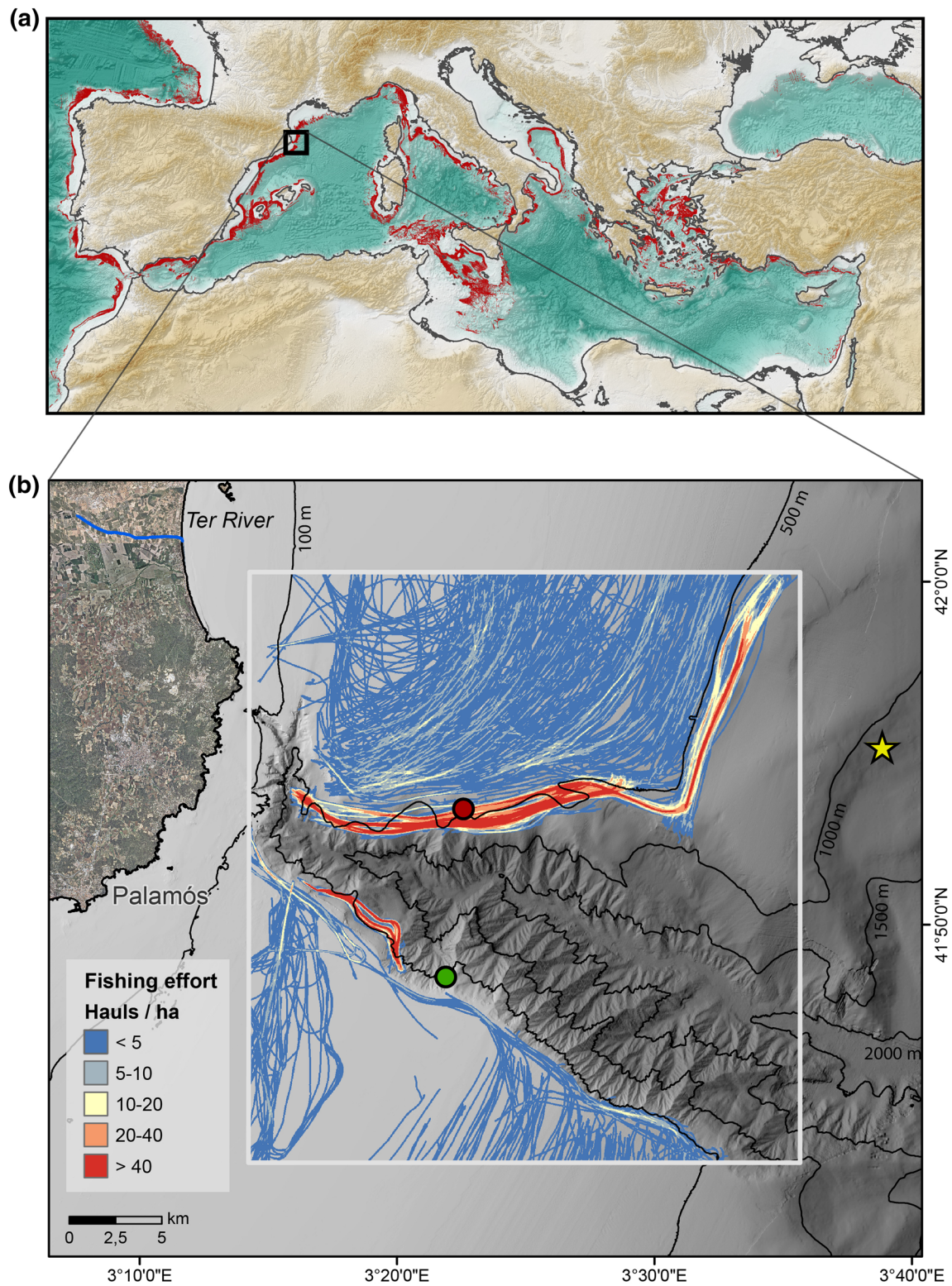


Figure 1. Bottom trawling grounds (red) on continental slopes of the Mediterranean Sea and surrounding margins (a). Bathymetric map of Palamós Canyon and cumulative bottom trawling fishing effort computed from February 2017 to March 2018 (b). Circles indicate the sampling locations of sediment cores from the trawled (red) and untrawled (green) sites. The location of the Cap de Begur buoy is shown by a yellow star.

2. Materials and Methods

2.1. Sampling

Sampling was conducted during four cruises onboard the *R/V García del Cid* at contrasting seasons: during the temporal trawling closure in February 2017, during the trawling season in June and October 2017, and toward the end of the trawling closure in March 2018 (Figure S1 and Table S1). Sediment cores were collected using a K/C Denmark multicorer on the trawled northern flank of Palamós Canyon and on the untrawled southern flank at ~500-m depth (Figure 1b). When possible, duplicate sediment cores were collected from independent multicore deployments to account for spatial heterogeneity, although this was only possible during some cruises due to time restrictions and sea state conditions. Bad weather conditions in February 2017 only permitted the retrieval of one sediment core in the trawled site, whereas the untrawled site could not be sampled. From each deployment, the sediment core with the best preservation of the surface-water interface was sliced at 1-cm intervals on deck and stored at -20°C until lyophilization in the laboratory.

2.2. Analyses

Concentrations of ^{210}Pb were determined through alpha spectroscopy of the decay product ^{210}Po following the method described by Sánchez-Cabeza et al. (1998). Average sedimentation rates were calculated using excess ^{210}Pb concentrations over accumulated dry mass with depth following the Constant Flux: Constant Sedimentation model (Krishnaswamy et al., 1971). Concentrations of ^{226}Ra were obtained through the gamma ray emissions of its decay product ^{214}Pb using calibrated geometries in a well-type high-purity germanium gamma detector. Concentrations of ^{234}Th ($t_{1/2} = 24.1$ days) were measured by gamma spectrometry through its emission line at 63 keV within one half-life since sampling, restricting measurements of sediment cores to the upper 3–6 cm. Samples were remeasured after all excess ^{234}Th had decayed to obtain ^{238}U concentrations and quantify excess ^{234}Th concentrations. Gamma measurements also permitted the quantification of the short-lived cosmogenic radionuclide ^7Be ($t_{1/2} = 54$ days; 478 keV) and the artificial radionuclide ^{137}Cs ($t_{1/2} = 30$ years; 662 keV).

Dry bulk densities of sediment cores were calculated by dividing the net dry weight, after correcting for salt content, by the sample volume. Sediment grain size was measured using a Horiba Partica LA-950V2m particle-size analyzer by first oxidizing 1–4 g of dry sediment with H_2O_2 (20%) and disaggregating it using $\text{P}_2\text{O}_7^{2-}$ (2.5%) left overnight. Elemental analysis of total carbon, organic carbon (OC), and total nitrogen (TN) contents were carried out with an elemental analyzer (Costech ECS Analyzer-4010), following the procedure described by Nieuwenhuize et al. (1994). Inorganic carbon, quantified as the difference between total carbon and OC, was converted to CaCO_3 contents using the molecular mass ratio of 100/12. Dry bulk densities, sediment grain size, and elemental analyses were performed in the upper 10 cm of all sediment cores.

Sedimentary OC yields a suite of biomarkers upon alkaline CuO oxidation that can be grouped into lignin-derived phenols (vanillyl, syringyl, and cinnamyl phenols), cutin acids, benzoic acids, p-hydroxybenzenes, amino acid-derived products, di-carboxylic acids, and fatty acids (Table S2). These biomarkers have distinct chemical precursors and its origin can be classified as terrestrial and heterogenous, the latter as a result of a combination of both terrestrial and marine sources (Table S2). CuO oxidations were conducted at specific depths (0–1, 2–3, 4–5 cm) in all sediment cores following the method described by Goñi and Montgomery (2000). Individual reaction products (Table S2) were quantified through selective ion monitoring by gas chromatography-mass spectrometry using a Hewlett Packard 6890GC fitted with a HP5973 mass selective detector as previously described by Goñi et al. (2009).

2.3. Statistical Analysis

Permutational two-way analysis of variance was employed to assess whether there were statistical differences of all parameters between sites (trawled, untrawled), sampling season (June 2017, October 2017, and March 2018), and the interaction between site and sampling season, using 9,999 permutations. Since no untrawled core was collected in February 2017, the trawled sediment core was excluded from this analysis. This statistical analysis was performed for grain size, CaCO_3 , OC, TN, and OC/TN in the upper 10 cm of all

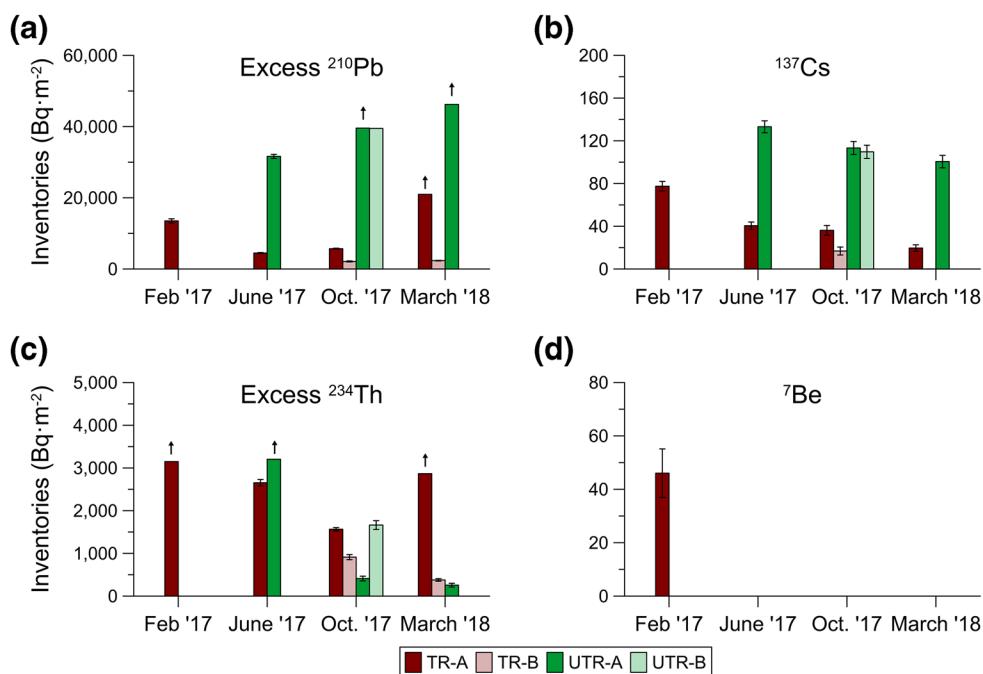


Figure 2. Inventories of excess ²¹⁰Pb (a), ¹³⁷Cs (b), excess ²³⁴Th (c), and ⁷Be (d) for trawled (red) and untrawled (green) sites. Arrows above excess ²¹⁰Pb and excess ²³⁴Th inventories indicate that supported concentrations were not reached, thus values must be regarded as lower estimates. Inventories for ¹³⁷Cs correspond to the upper 2.5 g·cm⁻² cumulative dry mass of each core to allow comparison. Be-7 was only detected in the top-most sediment of the February 2017 trawled core. Replicate cores are indicated by A and B codes.

sediment cores, and for CuO products in sections 0–1, 2–3, 4–5 cm of all sediment cores, including duplicate cores.

Principal components analysis (PCA) was performed on dry bulk density, grain size (proportion of sand, silt, and clay), as well as concentrations of OC, TN, CaCO₃, and CuO products in sections 0–1, 2–3, 4–5 cm of all sediment cores. To identify the variables that mostly determine trawled and untrawled samples, a linear discriminant analysis (LDA) was performed on the results of the PCA to find the boundary line that best separates these two classes. Both PCA and LDA were performed using Python's scikit-learn module (Pedregosa et al., 2011).

Methods employed to obtain information on fishing effort and environmental conditions are provided in the Texts S1 and S2.

3. Results and Discussion

3.1. Bottom Trawling Erodes the Seafloor

Sediment cores collected on the trawled site were generally depleted in excess ²¹⁰Pb and ¹³⁷Cs inventories in comparison to sediment cores collected on the untrawled site (Figures 2a and 2b), indicating a high degree of erosion by trawling activities. Two of the trawled sediment cores, February 2017 (TR-A) and March 2018 (TR-B), presented a deep penetration of excess ²¹⁰Pb and higher inventories than the remaining trawled cores (Figures 2a and S2), a trait attributed to either intense sediment mixing by trawling gear, and/or the lateral displacement of sediment observed in trawl marks (Martín et al., 2014a; Paradis et al., 2017, 2018).

In contrast, all untrawled sediment cores collected in the southern flank had high excess ²¹⁰Pb inventories (Figure 2). Their surface layers presented altered excess ²¹⁰Pb concentrations (Figure S2), which could indicate intense mixing or an increase in sedimentation rates associated with the lateral transport

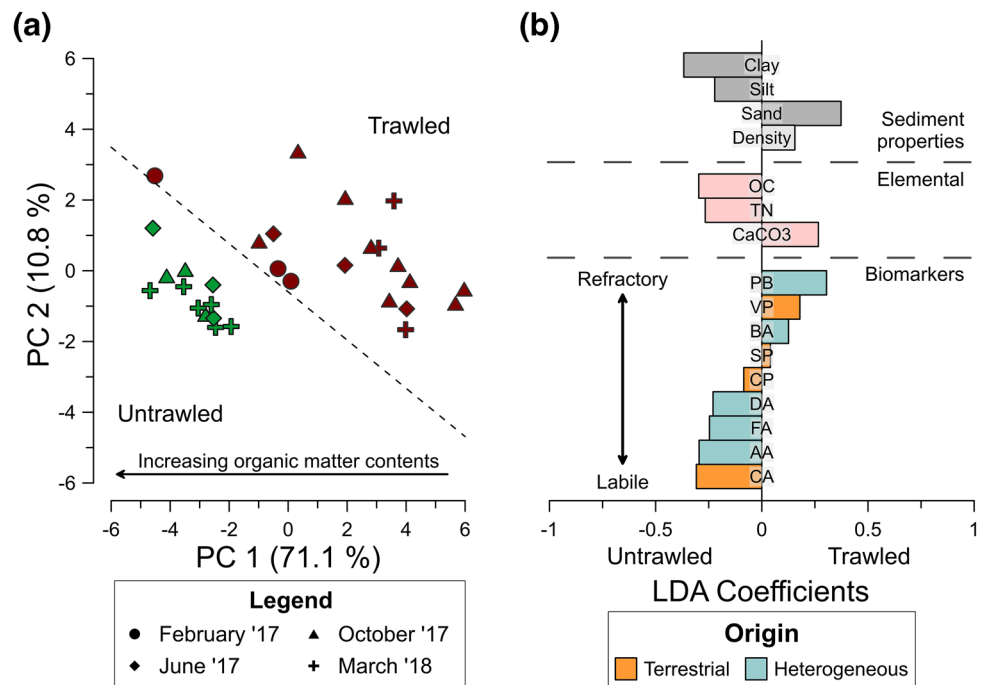


Figure 3. Multivariate analyses of sediments from trawled and untrawled sites. (a) PCA of sedimentological parameters (dry bulk density, grain size), elemental (CaCO_3 , OC, and TN) and CuO oxidation products in trawled (red) and untrawled (green) samples. The dashed line indicates the LDA boundary line separating trawled and untrawled samples. (b) LDA coefficients of all parameters. Abbreviations: VP, vanillyl phenols; SP, syringyl phenols; CP, cinnamyl phenols; CA, cutin acids; PB, p-hydroxybenzenes; BA, benzoic acids; AA, amino acids; DA, di-carboxylic acids; FA, fatty acids.

of resuspended sediment from trawling grounds (Martín et al., 2014c). Below these altered layers, exponentially decreasing excess ^{210}Pb concentration profiles allowed to estimate sedimentation rates of $0.37\text{--}0.85\text{ cm yr}^{-1}$ (Figure S2 and Table S2), in agreement with values previously reported in the area (Martín et al., 2014a).

With the exception of the sediment cores from February 2017 (TR-A) and March 2018 (TR-A), trawled sediment cores generally had comparable excess ^{210}Pb inventories and penetration depths during all sampling seasons (Figures 2a and S2), consistent with measurements from a sediment core collected in the same site in 2011 (core NF-4 in Martín et al. (2014a)). These similarities suggest that the rate of erosion in the northern flank of Palamós Canyon is relatively constant and is compensated by the rate of sediment accumulation in the area (0.33 and $0.63\text{ g cm}^{-2}\text{ yr}^{-1}$; Table S3). Hence, we can estimate that the rate of erosion ranges between 3 and $6\text{ kg m}^{-2}\text{ yr}^{-1}$, which, if extrapolated to the entire northern flank trawling ground (42 km^2), would amount to up to $125\text{--}250 \times 10^3$ tones of sediment eroded annually.

Despite the almost-daily trawling frequency on this fishing ground (Figure S1c), which erodes surface sediments, excess ^{234}Th inventories were generally similar in trawled and untrawled sites in each sampling period, with the exception of the thoroughly mixed March 2018 TR-A core (Figure 2c). Trawled sediment cores usually had shallower penetration depths and higher superficial excess ^{234}Th concentrations in comparison to untrawled sites (Table S2 and Figure S2). This fact suggests that some of the sediment resuspended by bottom trawlers is redeposited on fishing grounds, scavenging excess ^{234}Th from the water column in the process. This continuous resuspension and partial redeposition of sediments causes grain-size sorting through the selective advection of fine-grained sediment, whereas coarser sediment is preferentially redeposited. This process progressively increases dry bulk densities as well as the sand content of the trawled site (Figure S3), causing bed armoring effects (Martín et al., 2014a).

3.2. Bottom Trawling Hampers the Preservation of Organic Matter

Chronic and intense bottom trawling activities not only altered sedimentological properties, but also modified the biogeochemical composition of sediments through the relative enrichment of trawling grounds in CaCO_3 and the reduction of OC, TN, and biomarkers (Figures S4 and S5). Based on the results of the PCA, it is apparent that sediments in bottom trawling grounds have lower sedimentary organic matter content (Figure 3). The LDA coefficients highlight a particular impoverishment of labile biomarkers, such as amino acid-derived and fatty acid-derived compounds in trawled sediments, and a predominance of refractory compound classes such as p-hydroxybenzenes and vanillyl phenols (Figure 3b). Predominance of refractory terrestrial compounds in trawled samples was mostly driven by the surficial sediments of the trawled core retrieved in February 2017 after a Ter River flood (see Section 3.3 for more detail).

Bulk concentrations of elemental OC and TN in the trawled site were $\sim 30\%$ lower than in the untrawled site (Figure 4a). Similar differences were observed for the more refractory compound classes such as lignin phenols (vanillyl, syringyl, and cinnamyl phenols) and both p-hydroxybenzenes and benzoic acids (-24% to -33%). In contrast, the more labile compound classes such as di-carboxylic acids, fatty acids, amino acid-derived products, and cutin acids displayed considerably greater depletions (-52% to -70%) in the trawled site relative to the untrawled site consistent with enhanced losses (Figure 4a and Table S4).

The lower bulk organic matter contents in the trawled site could be due to winnowing of fine-grained sediments, which are typically characterized by higher organic matter content (e.g., Mayer, 1994; Smeaton & Austin, 2019; see Figure S6). After normalizing concentrations to clay and silt content, the differences between trawled and untrawled sites for the most refractory compound classes became insignificant (Figure 4b and Table S5), suggesting that removal of fine-grained sediments by winnowing is responsible for the losses of these compounds (Keil et al., 1998). However, even after normalizing by grain size, the trawled site cores still had significantly lower contents of OC, TN, and labile compounds than the untrawled cores (Figure 4b and Table S5), indicating that winnowing of organic matter-rich fine-grained sediment is not the only mechanism accounting for the lower organic matter content in the trawled site.

In fact, the compositional differences of sedimentary organic matter between trawled and untrawled sites obtained after normalizing biomarker concentrations to OC contents show that organic matter from both sites had comparable contents of the more refractory compounds, whereas the trawled site was still significantly impoverished in labile biomarkers (-31% to 69% ; Figure 4c and Table S6), suggesting a preferential degradation of these most reactive compounds. This degradation could be driven by greater sediment mixing by bottom trawling gear (Ferguson et al., 2020; van de Velde et al., 2018), which would be enhanced by increasing the permeability of the seafloor with coarser sediment (e.g., Keil, 2017; Rao et al., 2007). Additionally, the shift of benthic community structure in this trawling ground to more opportunistic life strategies (Pusceddu et al., 2014) points to a rapid and efficient degradation of nutritious organic matter, as observed in other deep-sea trawling grounds (Paradis et al., 2019).

The lower contents of all organic matter compound classes in trawled sediment cores indicate that bottom trawling removes the organic carbon stock from trawled continental slope sediments, through the erosion of organic matter-rich fine-grained sediment and the enhanced degradation of the more labile compounds.

3.3. Bottom Trawling Causes Persistent Impacts on the Seafloor

Despite the statistically significant seasonal variations of certain biomarker contents, the impacts caused by bottom trawling generally persisted throughout the year, with a substantial impoverishment of organic matter in the trawled site in comparison to the untrawled site (Figure 4 and Tables S4–S6). Greater arrival of fresh sediment to the seafloor were recorded in February and June 2017, as evidenced by their high excess ²³⁴Th inventories (Figure 2c). Enhanced particle export during the spring phytoplankton bloom in May 2017 (Figure S1c) led to a slight increase in OC and TN contents in surficial sediments of both sites in June 2017 (Figure S4). On January 23, 2017, a strong storm produced significant wave heights greater than 6 m (Figure S1a) and a torrential Ter River discharge of $130 \text{ m}^3 \text{ s}^{-1}$ (Figure S1b). These type of winter storms, when combined with flash floods, can transport large volumes of particulate organic matter to deeper parts of the margin (Martin et al., 2006; Sánchez-Vidal et al., 2013). This event supplied high concentrations of

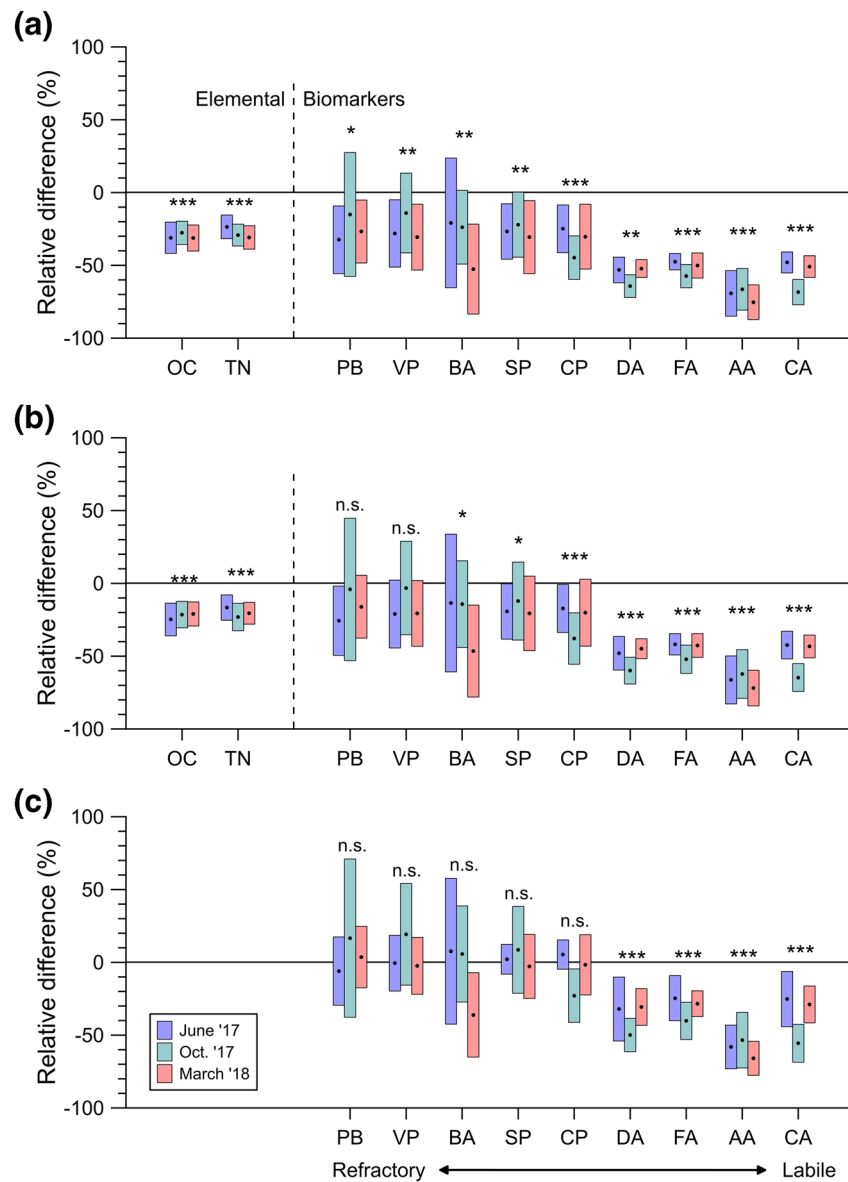


Figure 4. Relative difference in concentrations of organic matter compounds in trawled cores versus untrawled cores during the different sampling periods for bulk concentrations (a), after normalizing for fine-grained sediment (b), and after normalizing for OC contents (c). Dots indicate the average differences and the floating bars represent errors derived from standard deviations. Asterisks denote statistically significant differences between trawled and untrawled sites (Tables S4, S5, and S6): *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, and n.s., not significant.

the short-lived radionuclide ^7Be (Figure 2d) that were detected in surficial sediments two weeks later in the February 2017 core, as well as high concentrations of OC, TN, and biomarkers of terrestrial origin (i.e., cinnamyl phenols and cutin acids from nonwoody plant tissues and soil derived benzoic acids) (Figure S5). Despite the arrival of fresh organic matter by these natural processes, the contents of most biomarkers in the trawled site were always significantly lower than in the untrawled counterpart, a condition that prevailed even at the end of the trawling closure in March 2018 (Figure 4).

These results reveal that, although a 2-months seasonal trawling closure could allow fish stocks to rebuild (Martín et al., 2019), it is insufficient to restore the quantity and quality of organic matter in sediments of deep-sea trawling grounds. Indeed, with sedimentation rates of $0.37\text{--}0.85\text{ cm yr}^{-1}$ (Table S3), a trawling break of 2 months would only allow the accumulation of approximately $0.05\text{--}0.15\text{ cm}$ of sediment, which

cannot lead to measurable recoveries in these disturbed environments. With such low sedimentation rates, it would take between 10 and 30 years to accumulate at least 10 cm of sediment and slightly restore the seafloor. This period could actually be longer considering that trawled deep-sea sites have a greater dependence on the arrival of fresh and nutritious organic matter, which is rapidly consumed upon deposition (Paradis et al., 2019).

The slow rate of recovery of the sedimentary structure of the seabed and associated organic matter in trawled areas may inhibit the restoration of benthic communities at such depths (Clark et al., 2019; Goode et al., 2020). It is hypothesized that deep-sea environments would need around half a century to naturally recover from the damage exerted by bottom trawling (Da Ros et al., 2019), whereas shallower environments may present recoveries in a few weeks (Ferguson et al., 2020). Hence, the loss of organic carbon from trawling grounds on continental slopes, which are considered preferential carbon burial areas due to their large extension and infrequent natural disturbances (de Haas et al., 2002; Gordon & Goñi, 2004), may become irreversible.

The harmful effects of bottom trawling activities have been compared to forest clear-cutting on land (Wattling & Norse, 1998), but the effects of bottom trawling on the seafloor may be more akin to the effects of continuous plowing by intensive agricultural practices (Puig et al., 2012). In agricultural fields, tillage on land is responsible for 66–90 Gt of organic carbon lost due to accelerated erosion and mineralization (Lal, 2004), and our results indicate that a similar and comparable effect occurs on the seafloor due to chronic and intensive bottom trawling activities. Using the ~4.4 million km² spatial coverage of world continental slope trawling grounds (Puig et al., 2012) and the global distribution of sediment OC stock (Atwood et al., 2020), these fishing grounds are estimated to store ~20 Pg of OC in the upper meter. Assuming that ~30% of OC preserved in sediments is lost by bottom trawling, ~60 Gt of OC could have been removed from deep-sea trawling grounds, considering only the upper-most centimeter of the seabed. These estimates could be even greater taking into account that bottom trawling gear often penetrates deeper into the sediment (Oberle et al., 2016b). However, bottom trawling continues to intensify and expand to new unexploited grounds, with little regulation on the type of gear used and with the implementation of ineffective management strategies, such as seasonal trawling closures. Considering the wide extension of bottom trawling grounds and their continuous expansion to deeper areas, the disturbances by bottom trawling could be causing extensive and long-lasting impacts on the seafloor, leading to the release of vast amounts of carbon stored in deep-sea sediments. While more studies are needed to fully understand its implications and the magnitude of these impacts as a driver for global change, our findings are a clear indication of the severity and potential global implications of this fishing practice.

Acknowledgments

The authors would like to thank the crew of the R/V García del Cid, as well as Elena Martínez, Neus Maestro, and Silvia de Diago, who helped collect the samples. The authors are also grateful to Miquel Junyent for his help programming the fishing effort algorithm and to the Spanish Ports Authority for the access to AIS data. This study was funded by the “Assessment of Bottom-trawling Impacts in the Deep-sea Sediments” (ABIDES) Spanish Research Project (CTM2015-65142-R). Additional funds were provided by the Generalitat de Catalunya (2017 SGR-663 and SGR-1588), by the Australian Research Council LIEF Project (LE170100219) and by the Spanish Research Project ABRIC (RTI2018-096434-B-I00). This work is contributing to the ICTA’s “Unit of Excellence” Maria de Maetzu (CEX2019-000940-M), and ICM’s “Center of Excellence” Severo Ochoa (CEX2019-000928-S). The IAEA is grateful for the support provided to its Environment Laboratories by the Government of the Principality of Monaco.

Data Availability Statement

Data sets for this research are available in Paradis et al. (2020) at <https://ddd.uab.cat/record/225679>.

References

- Armstrong, M. P., Dean, M. J., Hoffman, W. S., Zemeckis, D. R., Nies, T. A., Pierce, D. E., et al. (2013). The application of small scale fishery closures to protect Atlantic cod spawning aggregations in the inshore Gulf of Maine. *Fisheries Research*, 141, 62–69. <https://doi.org/10.1016/J.FISHRES.2012.09.009>
- Atwood, T. B., Witt, A., Mayorga, J., Hammill, E., & Sala, E. (2020). Global patterns in marine sediment carbon stocks. *Frontiers of Marine Science*, 7(165), 1–9. <https://doi.org/10.3389/fmars.2020.00165>
- Bauer, J. E., Cai, W.-J., Raymond, P. A., Bianchi, T. S., Hopkinson, C. S., & Regnier, P. A. G. (2013). The changing carbon cycle of the coastal ocean. *Nature*, 504(7478), 61–70. <https://doi.org/10.1038/nature12857>
- Bjorkan, M., Company, J. B., Gorelli, G., Sardà, F., & Massaguer, C. (2020). *When fishermen take charge: The development of a management plan for the red shrimp fishery in Mediterranean Sea (NE Spain)* (pp. 159–178). Cham: Springer. https://doi.org/10.1007/978-3-030-26784-1_10
- Clark, M. R., Bowden, D. A., Rowden, A. A., & Stewart, R. (2019). Little evidence of benthic community resilience to bottom trawling on seamounts after 15 years. *Frontiers in Marine Science*, 6, 63. <https://doi.org/10.3389/fmars.2019.00063>
- Clark, M. R., Vinnichenko, V. I., Gordon, J. D. M., Beck-Bulat, G. Z., Kukharev, N. N., & Kakora, A. F. (2007). Large-scale distant-water trawl fisheries on seamounts. In *Seamounts: Ecology, fisheries & conservation* (pp. 361–399). Oxford, UK: Blackwell Publishing Ltd. <https://doi.org/10.1002/9780470691953.ch17>
- Da Ros, Z., Dell’Anno, A., Morato, T., Sweetman, A. K., Carreiro-Silva, M., Smith, C. J., et al. (2019). The deep sea: The new Frontier for ecological restoration. *Marine Policy*, 108, 103642. <https://doi.org/10.1016/j.marpol.2019.103642>

- de Haas, H., van Weering, T. C. E., & de Stigter, H. (2002). Organic carbon in shelf seas: Sinks or sources, processes and products. *Continental Shelf Research*, 22(5), 691–717. [https://doi.org/10.1016/S0278-4343\(01\)00093-0](https://doi.org/10.1016/S0278-4343(01)00093-0)
- Dunne, J. P., Sarmiento, J. L., & Gnanadesikan, A. (2007). A synthesis of global particle export from the surface ocean and cycling through the ocean interior and on the seafloor. *Global Biogeochemical Cycles*, 21, GB4006. <https://doi.org/10.1029/2006GB002907>
- Eigaard, O. R., Bastardie, F., Hintzen, N. T., Buhl-Mortensen, L., Buhl-Mortensen, P., Catarino, R., et al. (2017). The footprint of bottom trawling in European waters: Distribution, intensity, and seabed integrity. *ICES Journal of Marine Science*, 74(3), 847–865. <https://doi.org/10.1093/icesjms/fsw194>
- Ferguson, A. J. P., Oakes, J., & Eyre, B. D. (2020). Bottom trawling reduces benthic denitrification and has the potential to influence the global nitrogen cycle. *Limnology and Oceanography Letters*, 5(3), 237–245. <https://doi.org/10.1002/lol2.10150>
- Fernandez-Arcaya, U., Ramirez-Llodra, E., Aguzzi, J., Allcock, A. L., Davies, J. S., Dissanayake, A., et al. (2017). Ecological role of submarine canyons and need for canyon conservation: A review. *Frontiers in Marine Science*, 4, 5. <https://doi.org/10.3389/fmars.2017.00005>
- Ferré, B., Durrieu de Madron, X., Estournel, C., Ulses, C., & Le Corre, G. (2008). Impact of natural (waves and currents) and anthropogenic (trawl) resuspension on the export of particulate matter to the open ocean. *Continental Shelf Research*, 28(15), 2071–2091. <https://doi.org/10.1016/j.csr.2008.02.002>
- Goñi, M. A., Aceves, H., Benitez-Nelson, B., Tappa, E., Thunell, R., Black, D. E., et al. (2009). Oceanographic and climatologic controls on the compositions and fluxes of biogenic materials in the water column and sediments of the Cariaco Basin over the Late Holocene. *Deep Sea Research Part I Oceanographic Research Papers*, 56(4), 614–640. <https://doi.org/10.1016/j.dsr.2008.11.010>
- Goñi, M. A., & Montgomery, S. (2000). Alkaline CuO oxidation with a microwave digestion system: Lignin analyses of geochemical samples. *Analytical Chemistry*, 72(14), 3116–3121. <https://doi.org/10.1021/ac991316w>
- Goñi, M. A., O'Connor, A., Kuzyk, Z. Z., Yunker, M., & Gobeil, C. (2013). Distribution and sources of organic matter in surface sediments across the North American Arctic margin. *Journal of Geophysical Research: Oceans*, 118, 4017–4035. <https://doi.org/10.1002/jgrc.20286>
- Goode, S. L., Rowden, A. A., Bowden, D. A., & Clark, M. R. (2020). Resilience of seamount benthic communities to trawling disturbance. *Marine Environmental Research*, 161, 105086. <https://doi.org/10.1016/j.marenvres.2020.105086>
- Gordon, E. S., & Goñi, M. A. (2004). Controls on the distribution and accumulation of terrigenous organic matter in sediments from the Mississippi and Atchafalaya river margin. *Marine Chemistry*, 92(1–4), 331–352. <https://doi.org/10.1016/J.MARCHEM.2004.06.035>
- Gorelli, G., Sardà, F., & Company, J. B. (2016). Fishing effort increase and resource status of the deep-sea red shrimp *Aristeus antennatus* (Risso 1816) in the northwest Mediterranean Sea since the 1950s. *Reviews in Fisheries Science & Aquaculture*, 24(2), 192–202. <https://doi.org/10.1080/23308249.2015.1119799>
- Hale, R., Godbold, J. A., Sciberras, M., Dwight, J., Wood, C., Hiddink, J. G., & Solan, M. (2017). Mediation of macronutrients and carbon by post-disturbance shelf sea sediment communities. *Biogeochemistry*, 135(1–2), 121–133. <https://doi.org/10.1007/s10533-017-0350-9>
- Hayes, D. J., Vargas, R., Alin, S., Conant, R. T., Hutyrá, L. R., Jacobson, A. R., et al. (2018). Chapter 19: Future of the North American carbon cycle. In N. Cavallaro, G. Shrestha, R. Birdsey, M. A. Mayes, R. Najjar, S. Reed, et al. (Eds.), *Second state of the carbon cycle report (SOC-CR2): A sustained assessment report* (pp. 760–809). Washington, DC: U.S. Global Change Research Program. <https://doi.org/10.7930/SOCCR2.2018.Ch19>
- Hedges, J. I., & Keil, R. G. (1995). Sedimentary organic matter preservation: An assessment and speculative synthesis. *Marine Chemistry*, 49(2–3), 81–115. [https://doi.org/10.1016/0304-4203\(95\)00008-F](https://doi.org/10.1016/0304-4203(95)00008-F)
- Keil, R. (2017). Anthropogenic forcing of carbonate and organic carbon preservation in marine sediments. *Annual Review of Marine Science*, 9, 151–172. <https://doi.org/10.1146/annurev-marine-010816-060724>
- Keil, R. G., Tsamakidis, E., Giddings, J. C., & Hedges, J. I. (1998). Biochemical distributions (amino acids, neutral sugars, and lignin phenols) among size-classes of modern marine sediments from the Washington coast. *Geochimica et Cosmochimica Acta*, 62(8), 1347–1364. [https://doi.org/10.1016/s0016-7037\(98\)00080-5](https://doi.org/10.1016/s0016-7037(98)00080-5)
- Krishnaswamy, S., Lal, D., Martin, J. M., & Meybeck, M. (1971). Geochronology of lake sediments. *Earth and Planetary Science Letters*, 11(1–5), 407–414. [https://doi.org/10.1016/0012-821X\(71\)90202-0](https://doi.org/10.1016/0012-821X(71)90202-0)
- Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623–1627. <https://doi.org/10.1126/science.1097396>
- Legge, O., Johnson, M., Hicks, N., Jickells, T., Diesing, M., Aldridge, J., et al. (2020). Carbon on the northwest European shelf: Contemporary budget and future influences. *Frontiers in Marine Science*, 7, 143. <https://doi.org/10.3389/fmars.2020.00143>
- Martin, P., Maynou, F., Garriga-Panisello, M., Ramirez, J., Recasens, L., & Recasens, L. (2019). Fishing effort alternatives for the management of demersal fisheries in the western Mediterranean. *Scientia Marina*, 83(4), 293. <https://doi.org/10.3989/scimar.04937.29B>
- Martin, J., Palanques, A., & Puig, P. (2006). Composition and variability of downward particulate matter fluxes in the Palamós submarine canyon (NW Mediterranean). *Journal of Marine Systems*, 60, 75–97. <https://doi.org/10.1016/j.jmarsys.2005.09.010>
- Martin, J., Palanques, A., & Puig, P. (2007). Horizontal transfer of suspended particulate matter in the Palamós submarine canyon. *Journal of Marine Research*, 65(2), 193–218. <https://doi.org/10.1357/00224007780882569>
- Martin, J., Puig, P., Masqué, P., Palanques, A., & Sánchez-Gómez, A. (2014a). Impact of bottom trawling on deep-sea sediment properties along the flanks of a submarine canyon. *PLoS ONE*, 9(8), e104536. <https://doi.org/10.1371/journal.pone.0104536>
- Martin, J., Puig, P., Palanques, A., & Giampartone, A. (2014b). Commercial bottom trawling as a driver of sediment dynamics and deep seascape evolution in the Anthropocene. *Anthropocene*, 7, 1–15. <http://dx.doi.org/10.1016/j.ancene.2015.01.002>
- Martin, J., Puig, P., Palanques, A., & Ribó, M. (2014c). Trawling-induced daily sediment resuspension in the flank of a Mediterranean submarine canyon. *Deep Sea Research Part II: Topical Studies in Oceanography*, 104, 174–183. <https://doi.org/10.1016/j.dsr2.2013.05.036>
- Mayer, L. M. (1994). Relationships between mineral surfaces and organic carbon concentrations in soils and sediments. *Chemical Geology*, 114, 347–363. [https://doi.org/10.1016/0009-2541\(94\)90063-9](https://doi.org/10.1016/0009-2541(94)90063-9)
- Nieuwenhuize, J., Maas, Y. E. M., & Middelburg, J. J. (1994). Rapid analysis of organic carbon and nitrogen in particulate materials. *Marine Chemistry*, 45(3), 217–224. [https://doi.org/10.1016/0304-4203\(94\)90005-1](https://doi.org/10.1016/0304-4203(94)90005-1)
- Norse, E. A., Brooke, S., Cheung, W. W. L., Clark, M. R., Ekeland, I., Froese, R., et al. (2012). Sustainability of deep-sea fisheries. *Marine Policy*, 36(2), 307–320. <https://doi.org/10.1016/J.MARPOL.2011.06.008>
- Oberle, F. K. J., Puig, P., & Martin, J. (2018). Fishing activities. In *Submarine geomorphology* (pp. 503–534). Cham: Springer. https://doi.org/10.1007/978-3-319-57852-1_25
- Oberle, F. K. J., Storlazzi, C. D., & Hanebuth, T. J. J. (2016a). What a drag: Quantifying the global impact of chronic bottom trawling on continental shelf sediment. *Journal of Marine Systems*, 159, 109–119. <https://doi.org/10.1016/j.jmarsys.2015.12.007>
- Oberle, F. K. J., Swarzenski, P. W., Reddy, C. M., Nelson, R. K., Baasch, B., & Hanebuth, T. J. J. (2016b). Deciphering the lithological consequences of bottom trawling to sedimentary habitats on the shelf. *Journal of Marine Systems*, 159, 120–131. <https://doi.org/10.1016/j.jmarsys.2015.12.008>

- O'Neill, F. G., & Ivanović, A. (2016). The physical impact of towed demersal fishing gears on soft sediments. *ICES Journal of Marine Science: Journal Du Conseil*, 73(Suppl 1), i5–i14. <https://doi.org/10.1093/icesjms/fsv125>
- Palanques, A., García-Ladona, E., Gomis, D., Martín, J., Marcos, M., Pascual, A., et al. (2005). General patterns of circulation, sediment fluxes and ecology of the Palamós (La Fonera) submarine canyon, northwestern Mediterranean. *Progress in Oceanography*, 66(2–4), 89–119. <https://doi.org/10.1016/j.poccean.2004.07.016>
- Palanques, A., Puig, P., Guillén, J., Demestre, M., & Martín, J. (2014). Effects of bottom trawling on the Ebro continental shelf sedimentary system (NW Mediterranean). *Continental Shelf Research*, 72, 83–98. <https://doi.org/10.1016/j.csr.2013.10.008>
- Paradis, S., Goñi, M., Masqué, P., Durán, R., Arjona-Camas, M., Palanques, A., & Puig, P. (2020). *Sediment composition and radiochemical signature in trawled and untrawled flanks of Palamós Canyon, NW Mediterranean*. Barcelona, Spain: Universitat Autònoma de Barcelona. <https://doi.org/10.5565/ddd.uab.cat/225679>
- Paradis, S., Puig, P., Masqué, P., Juan-Díaz, X., Martín, J., & Palanques, A. (2017). Bottom-trawling along submarine canyons impacts deep sedimentary regimes. *Scientific Reports*, 7, 43332. <https://doi.org/10.1038/srep43332>
- Paradis, S., Puig, P., Sanchez-Vidal, A., Masqué, P., Garcia-Orellana, J., Calafat, A., & Canals, M. (2018). Spatial distribution of sedimentation-rate increases in Blanes Canyon caused by technification of bottom trawling fleet. *Progress in Oceanography*, 169, 241–252. <https://doi.org/10.1016/j.poccean.2018.07.001>
- Paradis, S., Pusceddu, A., Masqué, P., Puig, P., Moccia, D., Russo, T., & Lo Iacono, C. (2019). Organic matter contents and degradation in a highly trawled area during fresh particle inputs (Gulf of Castellammare, southwestern Mediterranean). *Biogeosciences*, 16(21), 4307–4320. <https://doi.org/10.5194/bg-16-4307-2019>
- Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., et al. (2011). Scikit-learn: Machine learning in Python. *Journal of Machine Learning Research*, 12, 2825–2830.
- Puig, P., Canals, M., Company, J. B., Martín, J., Amblas, D., Lastras, G., & Palanques, A. (2012). Ploughing the deep sea floor. *Nature*, 489(7415), 286–289. <https://doi.org/10.1038/nature11410>
- Pusceddu, A., Bianchelli, S., Martín, J., Puig, P., Palanques, A., Masqué, P., & Danovaro, R. (2014). Chronic and intensive bottom trawling impairs deep-sea biodiversity and ecosystem functioning. *Proceedings of the National Academy of Sciences of the United States of America*, 111(24), 8861–8866. <https://doi.org/10.1073/pnas.1405454111>
- Pusceddu, A., Grémare, A., Escoubeyrou, K., Amouroux, J. M., Fiordelmondo, C., & Danovaro, R. (2005). Impact of natural (storm) and anthropogenic (trawling) sediment resuspension on particulate organic matter in coastal environments. *Continental Shelf Research*, 25(19–20), 2506–2520. <https://doi.org/10.1016/j.csr.2005.08.012>
- Rao, A. M. F., McCarthy, M. J., Gardner, W. S., & Jahnke, R. A. (2007). Respiration and denitrification in permeable continental shelf deposits on the South Atlantic Bight: Rates of carbon and nitrogen cycling from sediment column experiments. *Continental Shelf Research*, 27(13), 1801–1819. <https://doi.org/10.1016/j.csr.2007.03.001>
- Sánchez-Cabeza, J. A., Masqué, P., & Ani-Ragolta, I. (1998). Pb-210 and Po-210 analysis in sediments and soils by microwave acid digestion. *Journal of Radioanalytical and Nuclear Chemistry*, 227, 19–22. <https://doi.org/10.1007/bf02386425>
- Sanchez-Vidal, A., Higuera, M., Martí, E., Liqueste, C., Calafat, A., Kerhervé, P., & Canals, M. (2013). Riverine transport of terrestrial organic matter to the North Catalan margin, NW Mediterranean Sea. *Progress in Oceanography*, 118, 71–80. <https://doi.org/10.1016/j.poccean.2013.07.020>
- Sañé, E., Martín, J., Puig, P., & Palanques, A. (2013). Organic biomarkers in Deep-sea regions affected by bottom trawling: Pigments, fatty acids, amino acids and carbohydrates in surface sediments from the La Fonera (Palamós) canyon, NW Mediterranean Sea. *Biogeosciences*, 10(12), 8093–8108. <https://doi.org/10.5194/bg-10-8093-2013>
- Smeaton, C., & Austin, W. E. N. (2019). Where's the carbon: Exploring the spatial heterogeneity of sedimentary carbon in mid-latitude fjords. *Frontiers of Earth Science*, 7, 269. <https://doi.org/10.3389/feart.2019.00269>
- Tesi, T., Langone, L., Goñi, M. A., Wheatcroft, R. A., Miserocchi, S., & Bertotti, L. (2012). Early diagenesis of recently deposited organic matter: A 9-yr time-series study of a flood deposit. *Geochimica et Cosmochimica Acta*, 83, 19–36. <https://doi.org/10.1016/j.gca.2011.12.026>
- van de Velde, S., Van Lancker, V., Hidalgo-Martinez, S., Berelson, W. M., & Meysman, F. J. R. (2018). Anthropogenic disturbance keeps the coastal seafloor biogeochemistry in a transient state. *Scientific Reports*, 8(1), 5582. <https://doi.org/10.1038/s41598-018-23925-y>
- Watling, L., & Norse, E. A. (1998). Disturbance of the seabed by mobile fishing gear: A comparison to forest clearcutting. *Conservation Biology*, 12(6), 1180–1197. <https://doi.org/10.1046/j.1523-1739.1998.0120061180.x>
- Watson, R. A., & Morato, T. (2013). Fishing down the deep: Accounting for within-species changes in depth of fishing. *Fisheries Research*, 140, 63–65. <https://doi.org/10.1016/j.fishres.2012.12.004>

References from the Supporting Information

- Behrenfeld, M. J., & Falkowski, P. G. (1997). Photosynthetic rates derived from satellite-based chlorophyll concentration. *Limnology and Oceanography*, 42(1), 1–20. <https://doi.org/10.4319/lo.1997.42.1.0001>
- European Commission Fisheries & Maritime Affairs. (2014). *Fleet register on the net*. Retrieved from <http://ec.europa.eu/fisheries/fleet/index.cfm?method=Search.SearchAdvanced>
- Global Fishing Watch. (2020). *Datasets and code: Fishing effort*. Retrieved from <https://globalfishingwatch.org/datasets-and-code/fishing-effort/>
- Goñi, M. A., & Hedges, J. I. (1990). Cutin-derived CuO reaction products from purified cuticles and tree leaves. *Geochimica et Cosmochimica Acta*, 54, 3065–3072. [https://doi.org/10.1016/0016-7037\(90\)90122-2](https://doi.org/10.1016/0016-7037(90)90122-2)
- Goñi, M. A., & Hedges, J. I. (1995). Sources and reactivities of marine-derived organic matter in coastal sediments as determined by alkaline CuO oxidation. *Geochimica et Cosmochimica Acta*, 59, 2965–2981. [https://doi.org/10.1016/0016-7037\(95\)00188-3](https://doi.org/10.1016/0016-7037(95)00188-3)
- Harris, P. T., Macmillan-Lawler, M., Rupp, J., & Baker, E. K. (2014). Geomorphology of the oceans. *Marine Geology*, 352, 4–24. <https://doi.org/10.1016/j.margeo.2014.01.011>
- Hedges, J. I., & Mann, D. C. (1979). The characterization of plant tissues by their lignin oxidation products. *Geochimica et Cosmochimica Acta*, 43, 1803–1807. [https://doi.org/10.1016/0016-7037\(79\)90028-0](https://doi.org/10.1016/0016-7037(79)90028-0)
- Kroodsma, D. A., Mayorga, J., Hochberg, T., Miller, N. A., Boerder, K., Ferretti, F., et al. (2018). Tracking the global footprint of fisheries. *Science*, 359(6378), 904–908. <https://doi.org/10.1126/science.aao5646>

- Natale, F., Gibin, M., Alessandrini, A., Vespe, M., & Paulrud, A. (2015). Mapping fishing effort through AIS data. *PLoS ONE*, *10*(6), e0130746.
- Palanques, A., Martín, J., Puig, P., Guillén, J., Company, J. B., & Sardà, F. (2006). Evidence of sediment gravity flows induced by trawling in the Palamós (Fonera) submarine canyon (northwestern Mediterranean). *Deep Sea Research Part I: Oceanographic Research Papers*, *53*(2), 201–214. <https://doi.org/10.1016/j.dsr.2005.10.003>
- Prahl, F., Ertel, J., Goni, M. A., Sparrow, M., & Eversmeyer, B. (1994). Terrestrial organic carbon contributions to sediments on the Washington margin. *Geochimica et Cosmochimica Acta*, *58*, 3035–3048. [https://doi.org/10.1016/0016-7037\(94\)90177-5](https://doi.org/10.1016/0016-7037(94)90177-5)